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Theoretical investigation of intraband absorption of electromagnetic radiation by holes in quantum wells

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Abstract. Using four-band Kane model we calculate intraband absorption coefficient of light by holes followed by their transition to the spin-orbital split-off band for $A_{III}B_V$ semiconductor quantum wells. It is shown that such an absorption mechanism is possible without any participation of a third particle like a phonon or an impurity and this mechanism can give the major contribution to the absorption of light in semiconductor quantum well lasers.

Introduction

It is common to believe that light absorption in semiconductor heterostructures by free carriers is weak, being possible only if together with electron-photon interaction a simultaneous scattering of an electron or hole on some other particle like a phonon or an impurity is considered. Nevertheless strong intraband damping of radiation is observed in long wavelength laser structures, based on narrow band semiconductors at high temperatures [1, 2]. This damping results in eventual collapse of lasing. As the width of the active region decreases, intraband absorption becomes enhanced and in laser structures with quantum wells absorption coefficient can be up to tens of inverse centimeters. At the same time the estimates done for the absorption coefficient accompanied by scattering on phonons or impurities give smaller values then those experimentally observed [3–5].

In this paper it will be shown that photon annihilation can be due to pure interaction with a hole and this process doesn't require participation of a third particle. Restrictions on intraband light absorption by a hole imposed by quasimomentum conservation are lifted if the hole interacts with heteroboundaries. Due to breaking of translation invariance symmetry the hole wave function appears to be a wave packet including various values of longitudinal wave vector k_x. In this way quasimomentum conservation can be satisfied for an arbitrary excited-hole state.

1. Wave functions of SO-holes in a rectangular quantum well

For calculation of intraband absorption coefficient we will use four-band Kane model, which proved to reproduce electron and hole spectrum in $A_{III}B_V$ semiconductors with a sufficient accuracy. Such a calculation for a homogeneous semiconductor has been done in particular in [8]. Boundary conditions and wave functions for the heavy holes are given in [9, 10]. Spin-orbital split-off wave functions are to be constructed from two basis sspinors. Below we give x-coordinate dependence of one of them:

$$\begin{bmatrix} \dfrac{i\hbar\gamma(q^2+k^2)}{E_g+\delta-E}\cos kx\ \eta \\ k\sin kx\ \eta - \lambda q\cos kx\ \xi \\ -iq\cos kx\ \eta + i\lambda k\sin kx\ \xi \\ -\lambda k\sin kx\ \xi + \lambda q\cos kx\ \eta \end{bmatrix} \tag{1}$$

The origin of the hole energy E is at $\delta = \Delta/3$ below then the valence band edge inside the quantum well; k and q are the x- and lateral quasimomentum components, $\lambda = \delta/\left(E + \delta + \hbar^2(q^2 + k^2)/2m_h\right)$.

With a good approximation we can neglect by mixing of heavy and light hole branches with large wave vectors to the spin-orbital holes. Notice, that this approximation is different from using 2×2 model for description of SO-holes. The basis functions given above contain components with both $j = 1/2$ and $j = 3/2$, where j being the total angular momentum, see for example [11]. In this way we can considerably simplify procedure of finding both discrete and continuous spectrum and wave functions of SO-holes. Wave functions of the holes situating on such quasidiscrete energy levels exponentially decay away from the interface with the characteristic wave vector κ. The dispersion equation for these holes is as follows:

$$(\alpha\kappa \cot \frac{ka}{2} + k)\left(\alpha\kappa \tan \frac{ka}{2} - k\right) = q^2(\alpha\tilde{\lambda} + \lambda)^2, \tag{2}$$

where a is the quantum well width, U_c is the electron barrier height, $\tilde{\lambda}$ corresponds to λ in a wide band semiconductor and

$$\alpha = -\frac{E_g + \delta + U_c - E}{E_g + \delta - E}\frac{q^2 + k^2}{q^2 - \kappa^2}.$$

States with different parity don't separate and as the analysis shows wave spectrum is not parabolic. It is important to take this non-parabolicity into account when calculating intraband absorption coefficient [8]. The spectrum calculated without parabolic approximation is quite simple, curves $k(q)$ are almost the straight lines and the approximation $k(q) = \text{const}$ is nearly exact. This approximation considerably simplifies calculation of absorption coefficient.

2. Matrix element of optical transition

The matrix element of the optical transition between he states Ψ_h of a heavy hole and Ψ of a SO-hole is equal to:

$$M = \frac{\hbar e}{c}\gamma \int (\vec{A}_0, \Psi_{p,\text{h}}{}^{+})\Psi_s \, dx \tag{3}$$

We assume that the light absorption mostly occurs at narrow band region of the heterostructure, i.e. in a quantum well. Therefore in (3) we restrict integration to the region from $-a/2$ to $a/2$. As an example we explicitly provide one non-zero matrix element for a transition to discrete and continuous spectra:

$$M_{sed,x} = \frac{\hbar e}{c}\gamma H_1 q D_1 S_k \left(\frac{\sin(k_h - k)a/2}{k_h - k} + \frac{\sin(k_h + k)a/2}{k_h + k}\right)$$

$$M_{oc1,z} = -\frac{\hbar e}{c}\gamma H_2 k_h C_1 S_k \left(\frac{\sin(k_h - k)a/2}{k_h - k} - \frac{\sin(k_h + k)a/2}{k_h + k}\right)$$

Here $S_k = [\hbar\gamma(q^2 + k^2)]/(E_g + \delta - E)$ is the quantity proportional to s-component of the wave function of a spin-orbital hole in the quantum well, $H_1 = H_2 = 1/[\sqrt{a(q^2 + k_h^2)}]$ are the normalizing constants for heavy holes, D_2 and C_1 are those for a SO-hole. The

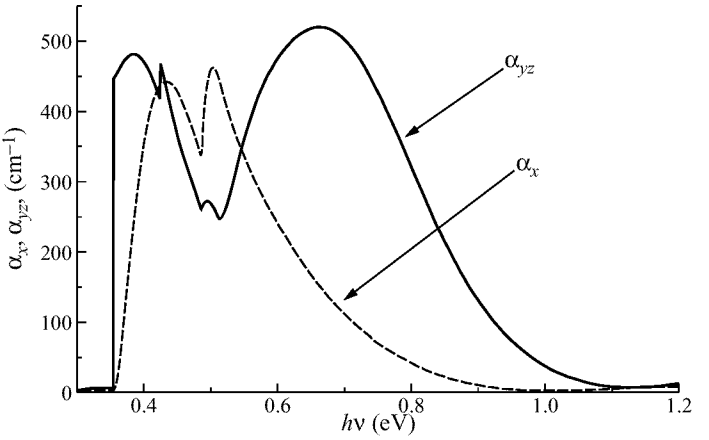

Fig. 1. Frequency dependence of absorption coefficients α_x and α_{yz}, $a = 50$ Å, $T = 250$ K.

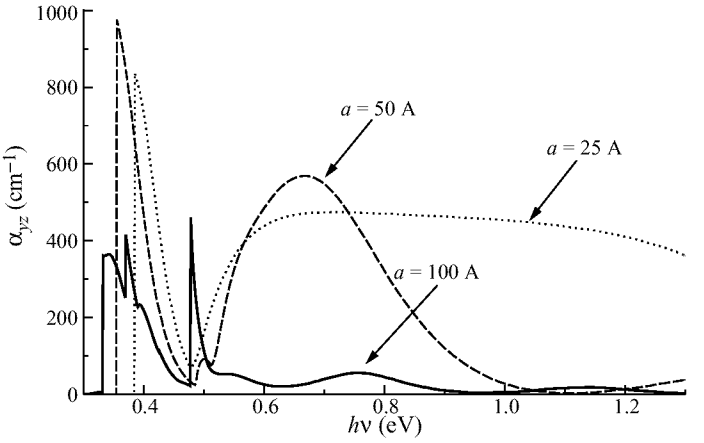

Fig. 2. Frequency dependence of absorption coefficient α_{yz} at different quantum well widths, $T = 100$ K.

number of transitions per unit time and unit length is equal to:

$$Q = 2\frac{2\pi}{\hbar}\sum_{k_h}\int_0^{\infty} q\,dq\int_0^{2\pi} d\varphi\left(\sum_{k(q)}\left|M_d^2\right| + \int_0^{\infty}\left(\left|M_{c1}^2\right| + \left|M_{c2}^2\right|\right)\frac{d\tilde{k}}{2\pi}2A\right)$$
$$\times f(E_h)\,\delta(E_h - E - \hbar\omega). \tag{4}$$

The multiplier of 2 reflects double degeneracy of energy levels. The rates Q_x and Q_{yz} corresponding to different initial polarization of the light are to be calculated separately. The corresponding rate for an arbitrarily polarized light can be obtained from

$$Q = Q_x\cos^2\beta + Q_{yz}\sin^2\beta, \tag{5}$$

where β is the angle between the vector potential $\vec{A}_0$ and x-axis. Direct calculations show that Q_x is less then Q_{yz} almost at all frequencies due to proportionality of M_x to the lateral

component of the quasimomenta q. By the same reason dependence of Q_x on temperature at constant density of holes in a well is stronger then that of Q_{yz}.

Figure 1 shows frequency dependence of absorption coefficients α_x and α_{yz} (other words of the rates Q_x and Q_{yz} divided by the quantum well width a and photon flux density) for different polarizations of the light at temperature of 250 K.

In numerical calculation we used the following parameters for the InGaAsP/InP quantum well: $E_g = 0.83$ ev, $\Delta = \widetilde{\Delta} = 0.32$ ev, $U_v = 0.213$ ev, $U_c = 0.136$ ev, $m_h = 0.45m$, $m_c = 0.041m$, $m_{so} = 0.15m$, $p = 10^{12}\,\mathrm{cm}^{-2}$.

For wide quantum wells, absorption coefficient stipulated by heavy hole transition into discrete SO states has an explicit resonant nature and considerably exceeds coefficient caused by the transitions into continuous spectrum. In narrow quantum wells absorption is mainly due to transitions into the continuous spectrum and frequency dependence of the absorption coefficient is smooth (Fig. 2). Also it was found that resonant absorption is strongly affected by the quasistationarity of SO energy levels and by the scattering of phonons, which cause decrease and broadening of the peaks.

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